

Using Neutron Star Observations to Constrain Nuclear Physics

Joseph A. Carlson,
Stefano Gandolfi, T-2

Astrophysical observations provide important constraints to nuclear physics. In the last few years, the observation of masses and radii of neutron stars became accurate enough to be directly used to test theoretical predictions of the neutron matter equation of state (EOS). On the other side, the combination of theoretical models with recent observations opens the way to the measurement of the nuclear symmetry energy and its slope with a higher accuracy than recent terrestrial experiments.

In the recent years, important progress has been made in the observation of neutron star properties. The accuracy of these observations is giving us the confidence to provide new constraints in nuclear physics. A very important achievement is the possibility of measuring the mass and radius of neutron stars simultaneously [1] because this opens the way to extract direct information on the neutron matter EOS around nuclear densities.

Up to moderate densities of about $2-3\rho_0$, being $\rho_0=0.16\text{ fm}^{-3}$, the nuclear saturation density, neutron star matter is composed of a gas of neutrons and few protons. The easier non-trivial model to study neutron star matter is provided by the EOS of pure neutron matter. On the theoretical

side, the development of Quantum Monte Carlo (QMC) methods opened the way to study properties of nuclear systems using nuclear Hamiltonians that reproduce scattering data and properties of light nuclei with high precision [2]. Using modern supercomputers the EOS of pure neutron matter can now be calculated ab initio in a fully non-perturbative scheme [3]. Once the EOS of neutron matter is known, it is possible to study the structure of neutron stars in terms of their mass and radius by solving the Tolman-Oppenheimer-Volkoff equations.

Recently, several works have been aimed at showing the connection between the neutron

matter EOS and the symmetry energy—that is, the difference between nuclear matter and neutron matter energy. The symmetry energy is the energy cost of the isospin-asymmetry in the homogeneous nucleonic matter. Several experimental facilities aim to measure the value of the

symmetry energy, which is a great challenge. Even without knowing the experimental setup in detail, a naive idea for explaining the difficulty of these experiments is that any kind of experiment measure properties of nuclei where the number of neutrons is similar, or in a moderate excess with respect to the number of protons. As a consequence, any attempt to extrapolate the results to the limit of infinite neutrons will make the result model-dependent. In the past year, we performed QMC simulations to investigate the role of the three-neutron force in neutron matter [4]. In our work we discussed the uncertainty of the three-neutron force model, and studied the uncertainty played in the EOS of neutron matter. This uncertainty pertains to the properties of neutron stars once the EOS is used as input. An important aspect of our work is that the uncertainty of the model of the three-neutron force is smaller than the current accepted range of the symmetry energy in terrestrial experiments. This is quite an important statement because the main systematic uncertainties will not be related to the model of neutron matter that we use. The EOS of neutron matter computed using QMC is shown in Fig. 1 [4]. Each band corresponds to a class of EOSs with a symmetry energy indicated in the legend and is compared to the result obtained with a two-body force only and combined with the Urbana IX three-body force.

The work in [4] suggests a convenient functional form of EOS useful to extract the symmetry energy and its slope around nuclear densities. This form of nuclear EOS has been combined with phenomenological models describing the high-density part of the EOS, and the various free parameters have been fit to the most recent neutron star observations [5]. The profile of a neutron star in terms of its mass-radius is shown in Fig. 2. The red and black bands correspond to the neutron star profile obtained from observations using two different models of the stellar matter at high-density, at the 1σ and 2σ (dashed lines). The observations are compared to the theoretical predictions obtained from the EOSs of Fig. 1.

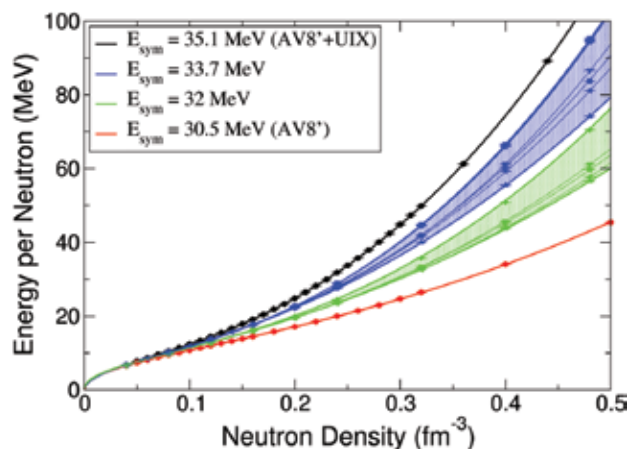


Fig. 1. The energy per particle of neutron matter corresponding to EOSs with symmetry energy indicated in the legend. Figure taken from [4].

The parameters extracted from the observations permit the derivation of the symmetry energy and its slope around the saturation density ρ^0 . The results are almost model-independent, and the associated error bars are smaller than the more recent experimental data. In Fig. 3 we show a comparison of L as a function of the symmetry energy S_0 (ESYM) obtained from neutron stars (indicated as “n-star”) with the most recent experimental constraints [6].

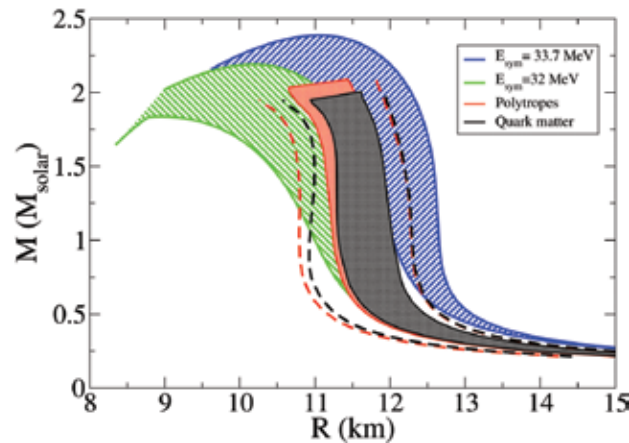


Fig. 2. The mass-radius relation of a neutron star obtained from the theoretical calculations (green and blue bands corresponding to the EOSs of Fig. 1) and from astrophysical observations red and black bands from [5].

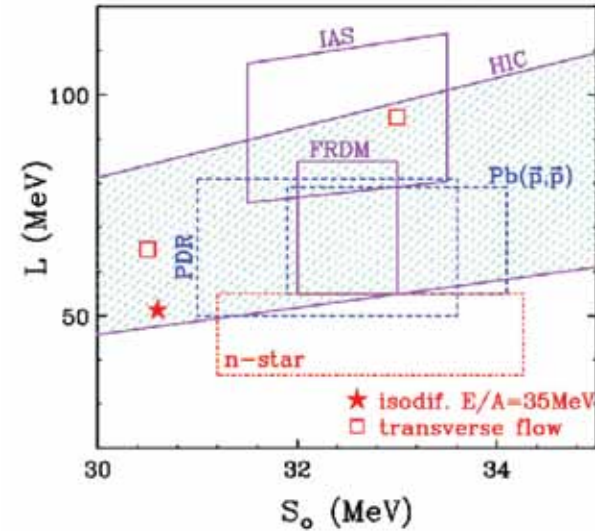


Fig. 3. Constraints of the slope L and magnitude S_0 (ESYM) of the symmetry energy at saturation density from different experiments and from neutron stars observations. Figure taken from [6].

- [1] Steiner, A.W. et al., *Astrophys J* **722**, 33 (2010).
- [2] Pieper, S.C., *AIP Conf. Proc.*, **1011**, 143 (2008).
- [3] Gandolfi, S. et al., *Phys Rev C* **79**, 054005 (2009).
- [4] Gandolfi, S. et al., *Phys Rev C* **85**, 032801 (2012).
- [5] Steiner, A.W. and S. Gandolfi, *Phys Rev Lett* **108**, 081102 (2012).
- [6] Tsang, M.B. et al., *Phys Rev C* **86**, 015803 (2012).